

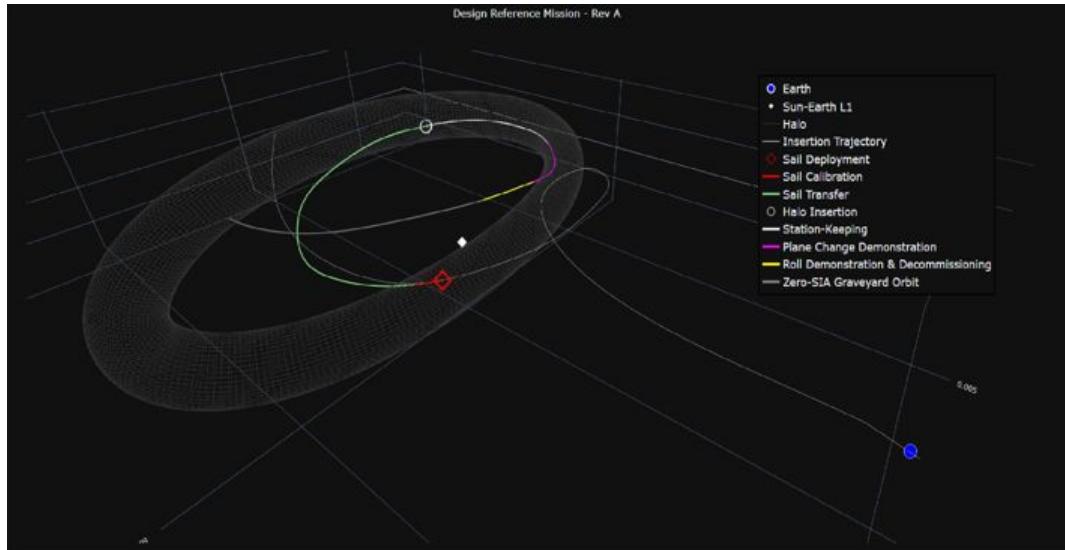
A Machine Learning Model for Solar Sail Reconstruction Using Flight Data

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Solar Cruiser Mission

- Solar sail demonstration mission
 - IMAP Secondary payload
 - 1653 m^2 sail area
- Objectives
 - Stationkeeping sunward of L1 libration point
 - Orbital transfer out of ecliptic plane



Problem Statement: Solar Sail Deflection

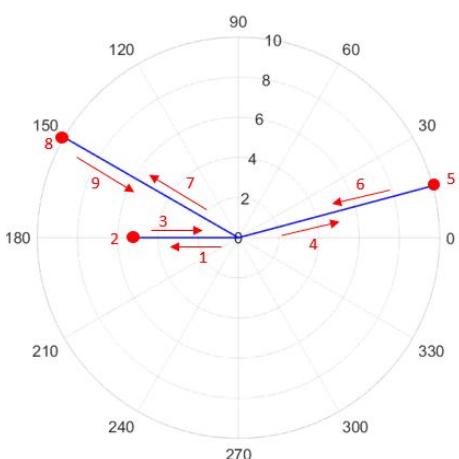
- Solar Cruiser boom and membrane deflection
 - Drives momentum management
- Context camera to examine 1 sail quadrant (2 booms)
- Goal: use attitude + disturbance torques to derive sail state
 - Inverse problem solution with neural network
 - Supplement/allow for context camera scope reduction (\$1.8M, 1.7 kg at PDR)



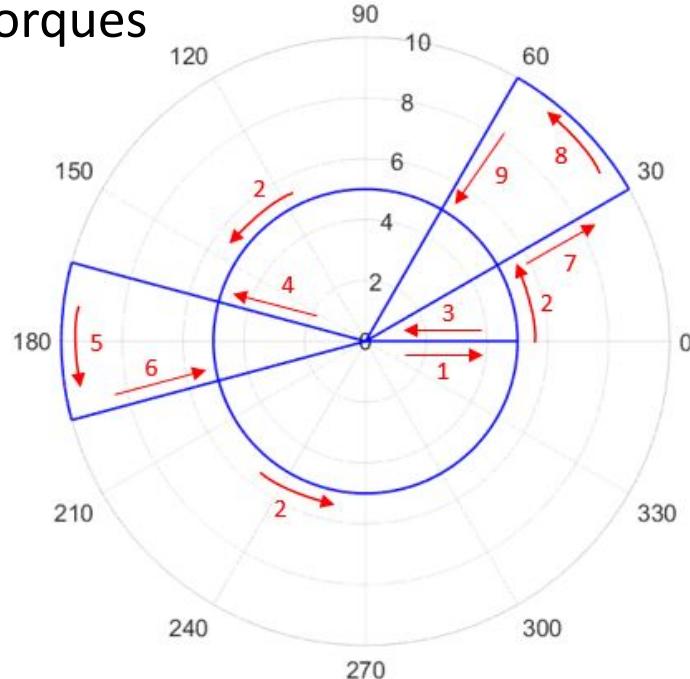
ConOps Sail Characterization

- Sail Characterization to find disturbance torques
- SIA: Sun Incidence Angle
- Roll, SIA, Clock sequence

$r = \text{SIA}$, $\theta = \text{roll}$

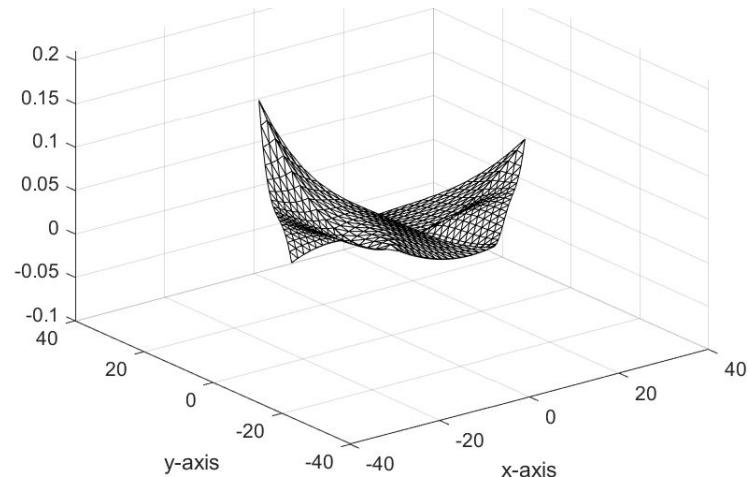


$r = \text{SIA}$, $\theta = \text{clock}$



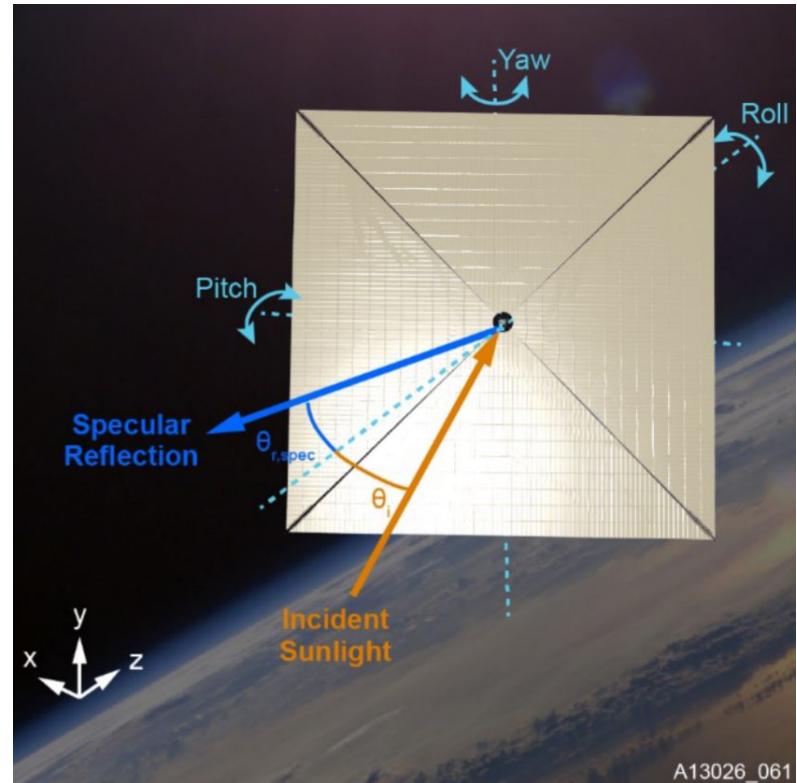
Dataset Generation

- Boom tip error values: Thermal, manufacturing, tension
- Membrane deflection, center of mass, boom tip deflection nominal + error
- Varying all boom tip and membrane deflection directions
- ~1.1 M shapes used in dataset training



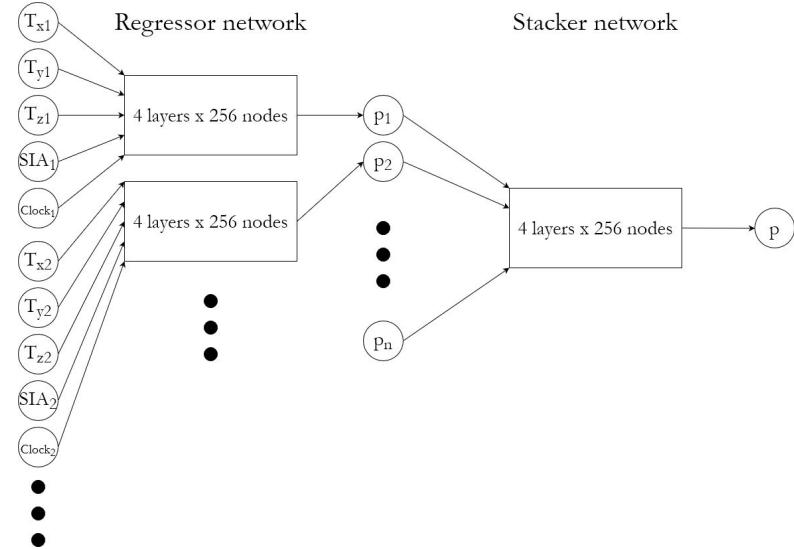
Sail Force and Torque Model

- Varied SIA and Clock in ConOps span, $\sim 100M$ cases
 - Processing power constraint
- Reduced-order sail characteristic tensor derived from shape file
- Sail torques and forces computed from tensor model

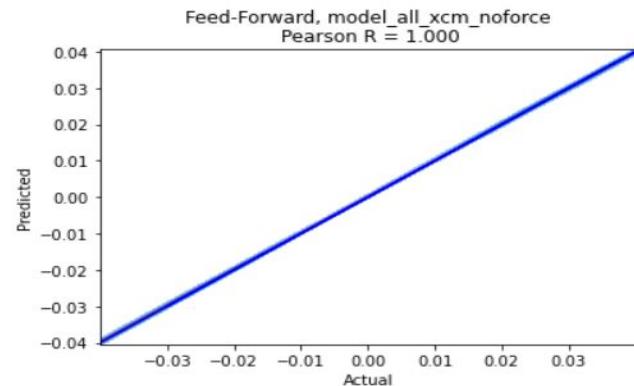
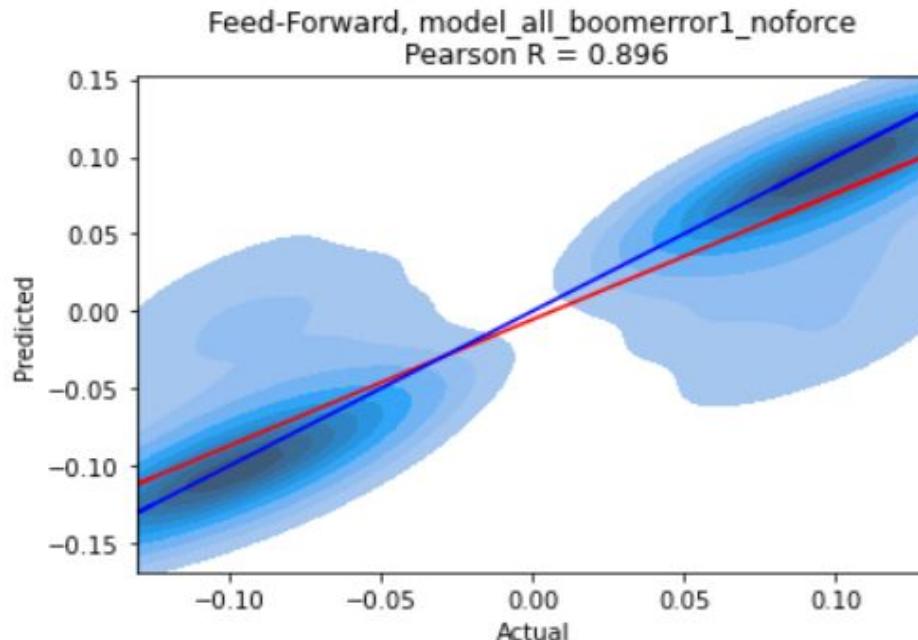


Network Architecture

- Inputs: Torque vector, SIA, Clock
- To predict Boom Tip Error, CM Error, Membrane Deflection (in single axis)
- Regressor and Stacker networks
 - 4 SELU Layers with 256 hidden nodes each
- Regressor Output: Prediction for single attitude
- Stacker Output: Prediction for entire characterization cycle



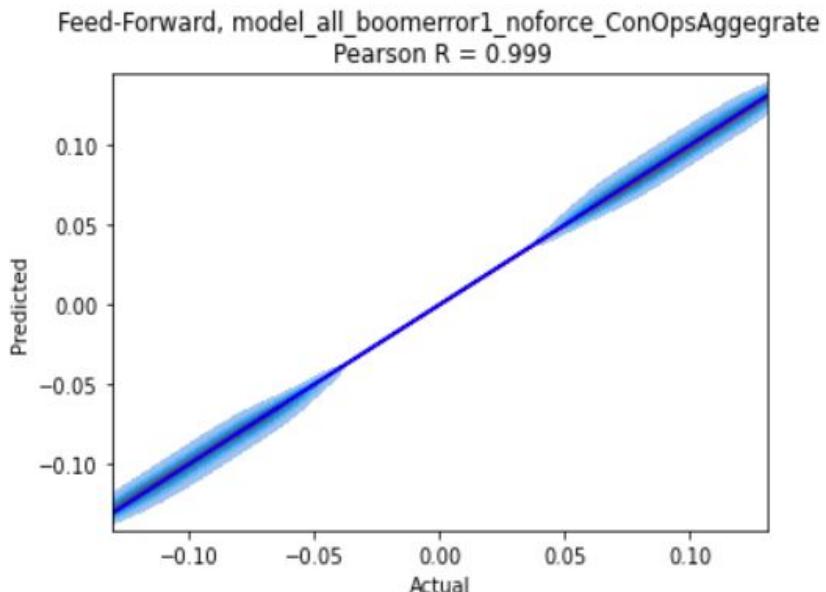
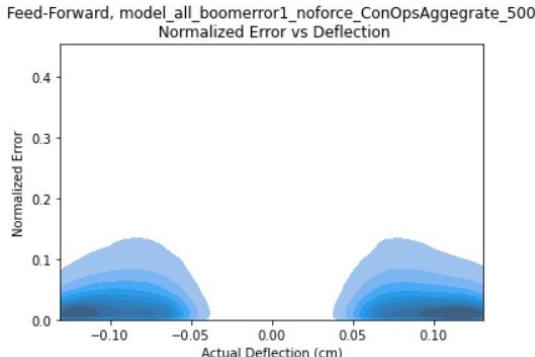
Network Performance: Regressor



Red: Best Fit, Blue: 1:1 correlation, each point is single shape + attitude

Network Performance: Stacker

- σ : stdev for normal distribution of deflection prediction error
- 3σ error: 1.38 cm
 - Regressor 3σ : 7.5 cm
 - Context Camera requirement: 3.81 cm
- 3σ Error Ratio: 14.3%



Discussion/Future Work

- Sensitivity testing to noise in attitude/torque measurements, sail shape model
 - Optimization of characterization sequence to maximize stacker performance
 - Applications to existing mission data, eg. NEA Scout
- Onboard autonomy for minimizing disturbance torques in flight

Summary

- Generated meshes for span of sail deflection states
- Found torques corresponding to meshes at various attitudes using tensor model
- Neural net predictions of deflections at individual attitudes
- Neural net combination of deflection predictions across simulated characterization sequence
- Enables:
 - Scope reduction for context camera
 - Validation of reduced order tensor sail modeling via extrapolation
 - Validation of sail shape parameters

Acknowledgements

Thank you to my mentor Daniel Tyler, the MSFC EV42 team, Sanjog Gururaj, and the NASA Office of STEM Engagement

Backup: Dataset Setup

- Nominal Boom Tip Deflection: 11 cases
- Error Boom Tip Deflection: 5 cases
- Membrane Deflection Error: 6 cases
- X/Y CM Offset: 7 cases each
- Boom/Membrane Deflection Direction: +/-, 4 directions each
- SIA: 1-10 deg in intervals of 1 deg
- Clock: 0-330 deg in intervals of 30 deg

Backup: Model Hyperparameters

- 4 Dense layers of 256 hidden SELU nodes each
- SELU nodes with Kaiming Normal initialization
- Adam optimization, 70%/30% train/test split, Mean Square Error Loss
- Regressor Net
 - Learning rate = 5×10^{-4}
 - Batch size = 2048
 - 10 Epochs
- Stacker Net
 - Learning rate = 1×10^{-3}
 - Batch size = 256
 - 500 Epochs